

# Evolution of Exozodiacal Disks

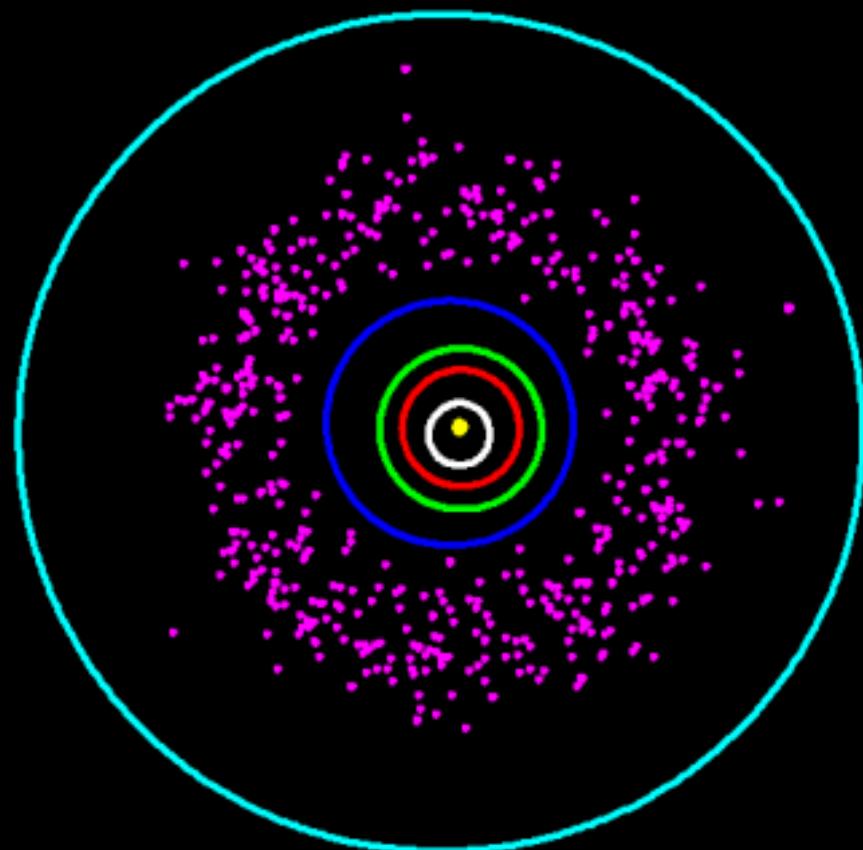
Scott Kenyon (SAO)

# Central Goals

- Simulate an entire solar system
- Links to other solar systems
  - \* Terrestrial planets
  - \* Jovian planets
  - \* Icy planets (Pluto, debris disks)

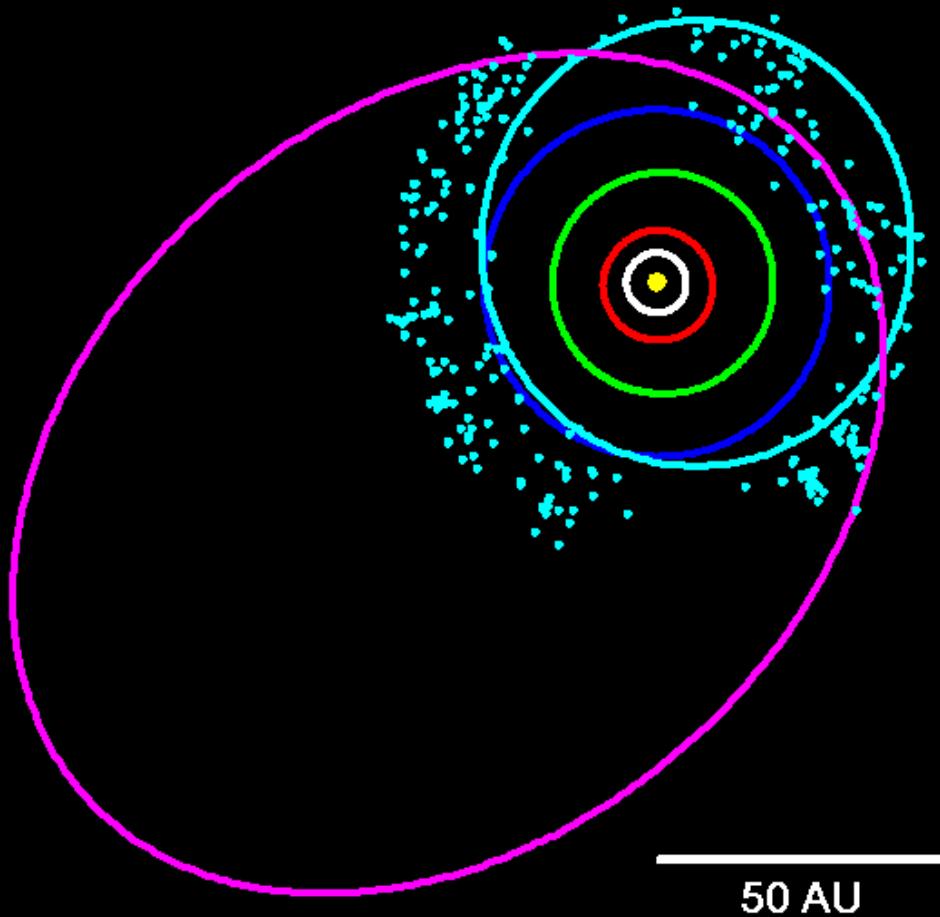
# Inner Solar System

## Top View



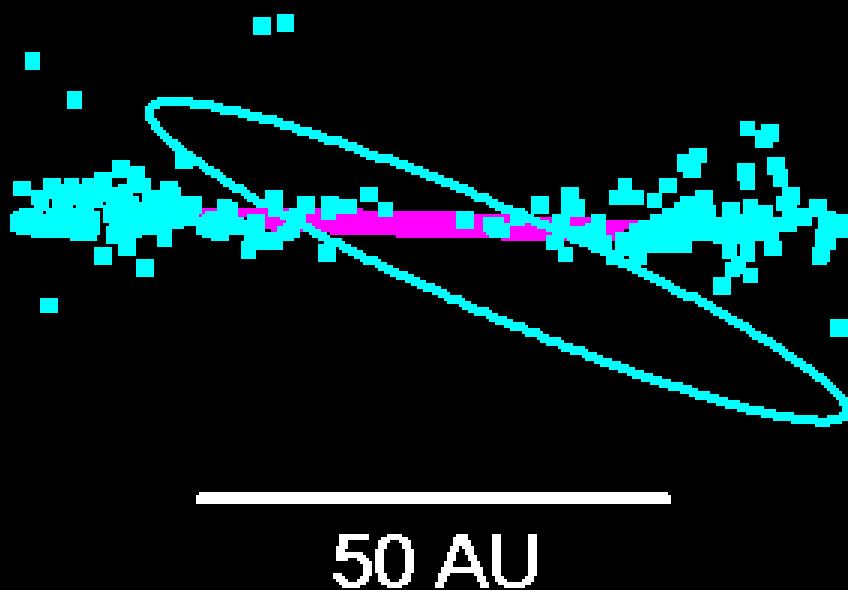
# Outer Solar System

## Top View



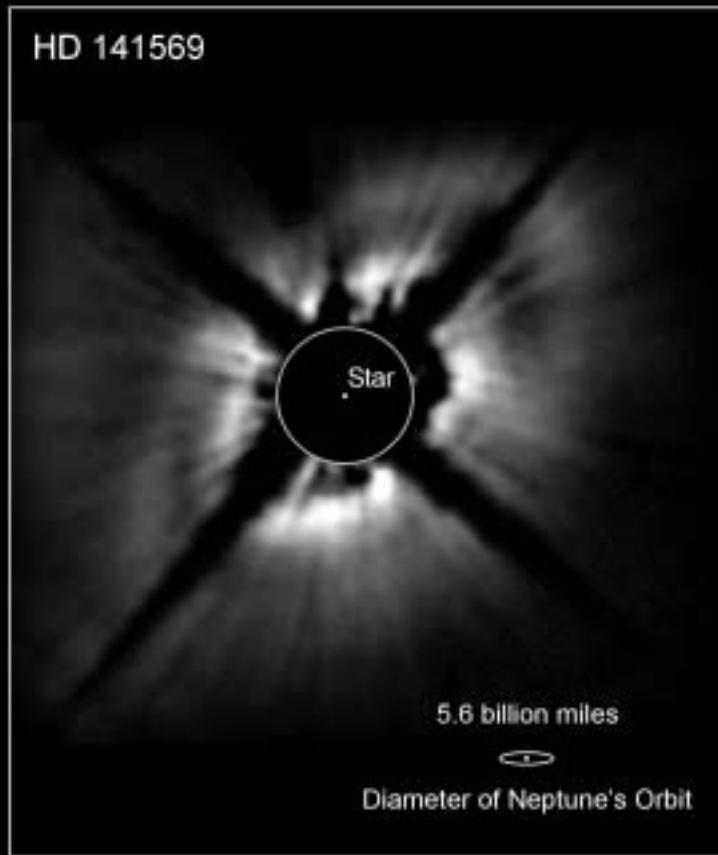
# Outer Solar System

## Side View

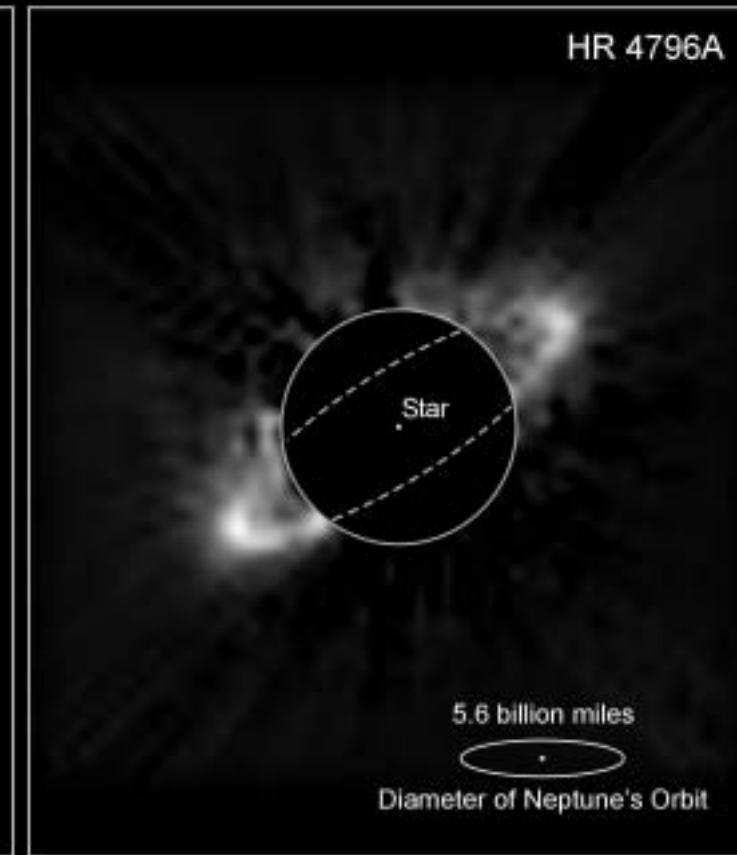


# Two Debris Disks

HD 141569

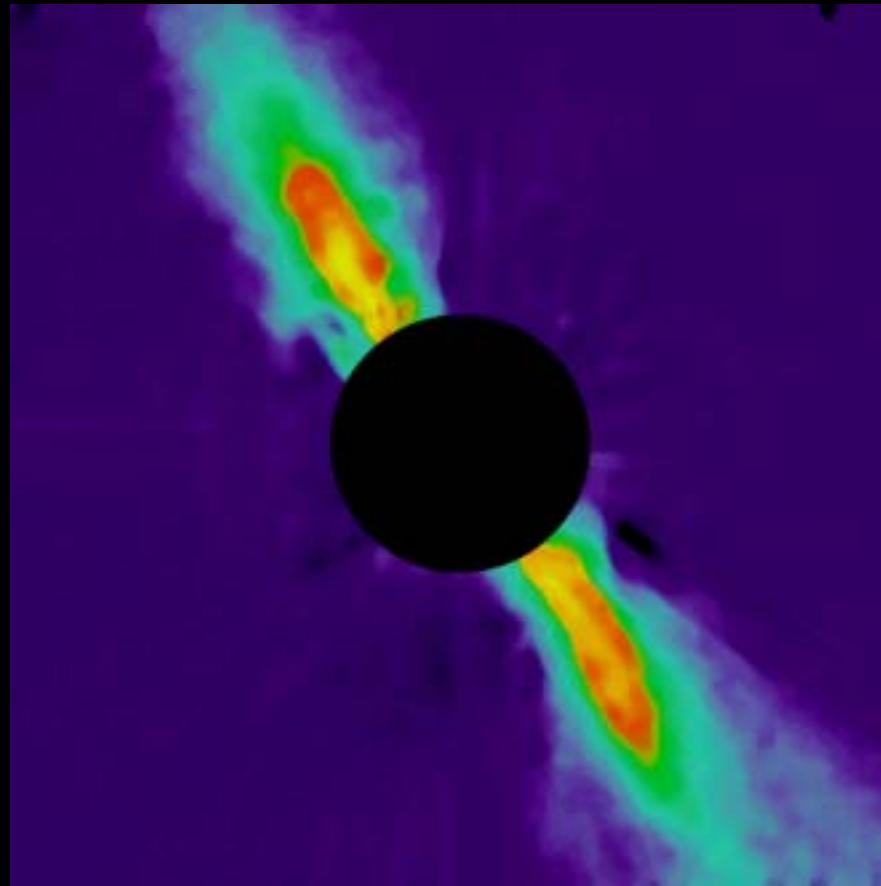


HR 4796A



**Dust Rings around Stars**  
Hubble Space Telescope • NICMOS

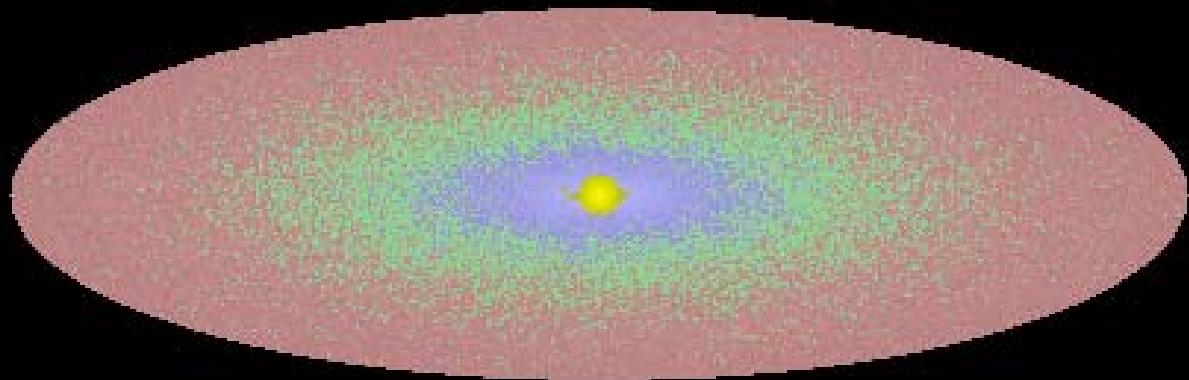
# $\beta$ Pictoris



Near-infrared – Lagrange et al

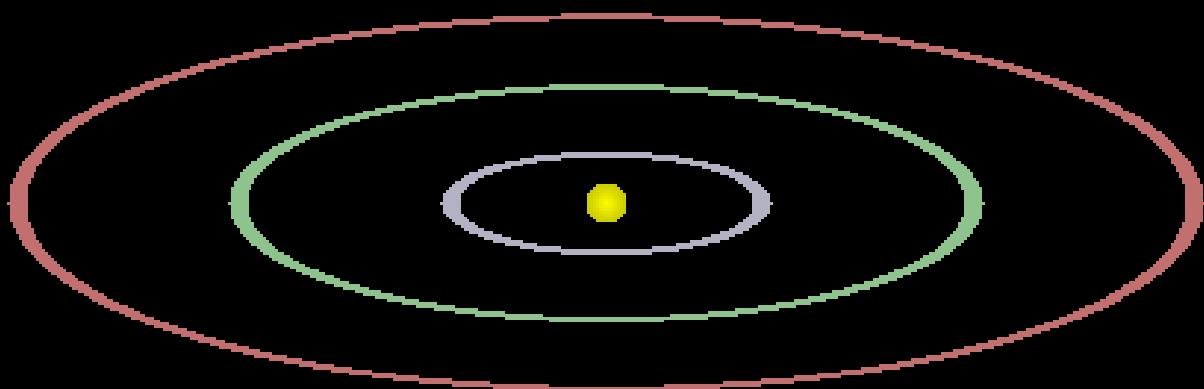
# A Dusty Disk

1 Myr



# A Solar System

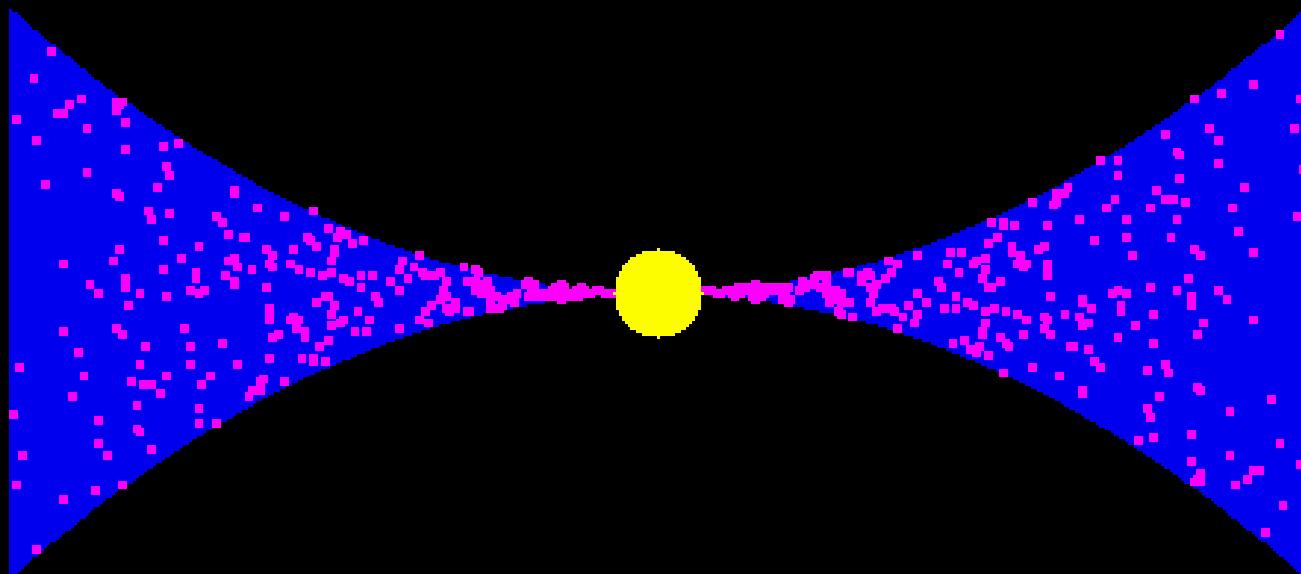
## 10-100 Myr



# Planets Grow in a Dusty Disk

\*disk radius = 100-1000 AU

\*disk mass =  $10^4 - 10^5 M_{\text{Earth}}$

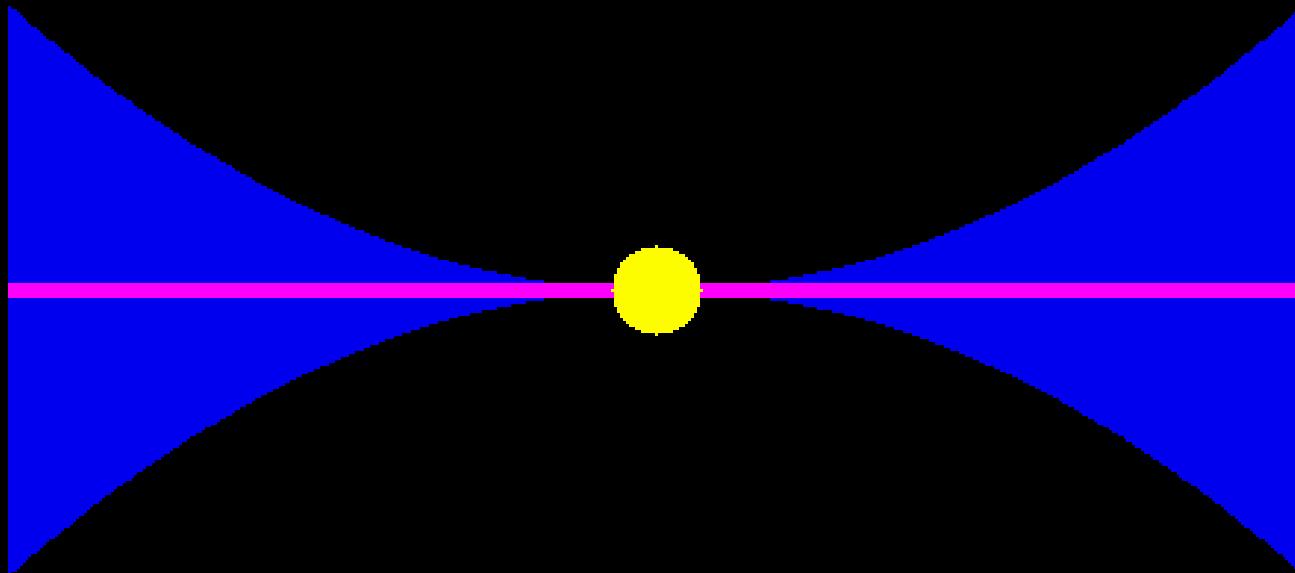


Safronov, Wetherill, Weidenschilling

# Dust Settles to Midplane

- \* 1 mm and larger particles

- \*circular orbits



# Planet Formation

- **Coagulation**
  - \* dust → planetesimals → planets + debris
  - \* make Earths
  - \* Earths accrete gas
  - \* Earths stir up debris
  - \* Debris scatters radiation from star
  - \* Scattered radiation is visible
- **Wetherill, Weidenschilling, Lissauer, ...**

# Highlights

- Successes
  - \* Earth-like planets in 10-30 Myr
  - \* Pluto-like planets in 10-100 Myr
  - \* Kuiper Belt properties
  - \* Vega-like debris disks
- Challenges
  - \* Jupiters are hard
  - \* Sedna

# Computing

- **Multiannulus coagulation code**
  - \* Fokker-Planck integrator
  - \* statistical collision solver
- **N-Body code (Bromley poster)**
  - \* follow individual trajectories
  - \* 8<sup>th</sup> order integrator
- **MPI Routines for Parallelization**
  - \* 40-50 cpu days per run

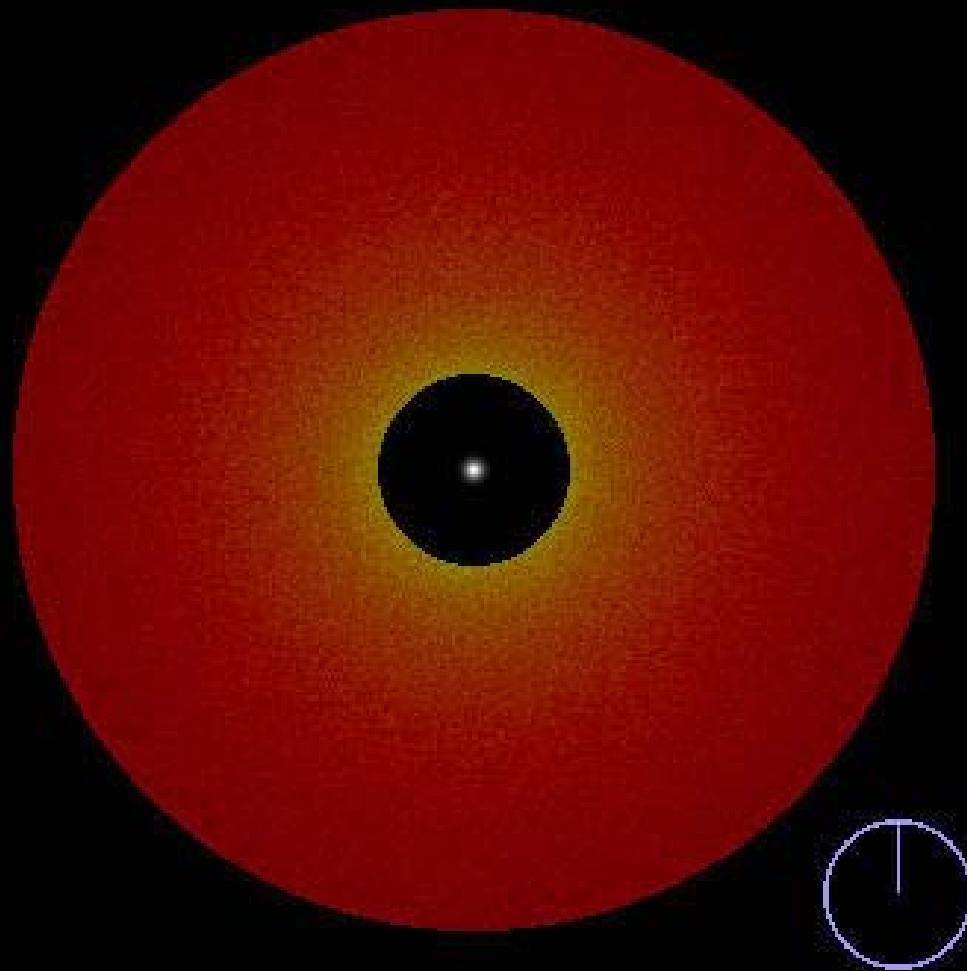
# Dust Images

- **Dust code**
  - \* dynamics from coagulation code
  - \* statistical collision solver
  - \* Poynting-Robertson + gas drag
  - \* radiation pressure
  - \* accurate for  $\tau_{\text{dust}} < 1-10$
- **Workstation**

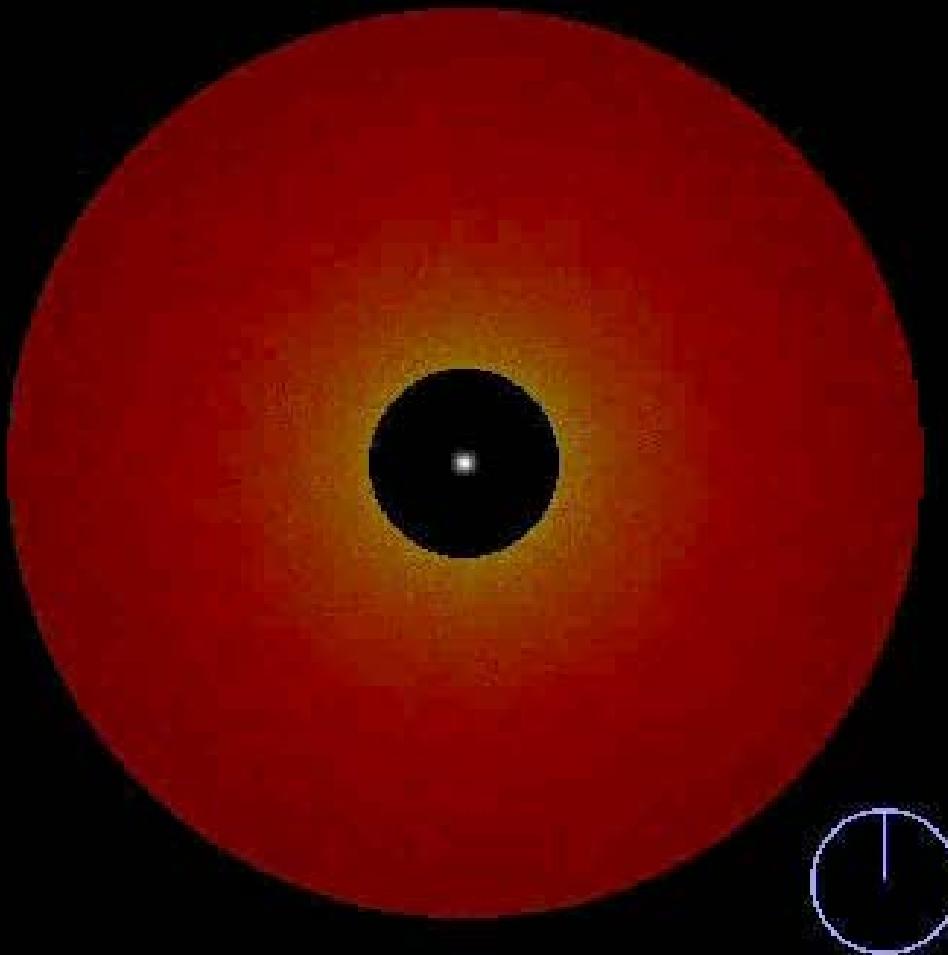
# Applications

- **Stellar Flybys**
  - \* Kenyon & Bromley AJ 121:538
- **Embedded Earth-mass planets**
  - \* Kenyon & Bromley AJ 127:513
  - \* Kenyon & Bromley ApJ 602: L133
- **Companion stars, large planets**
  - \* Kenyon & Bromley in preparation

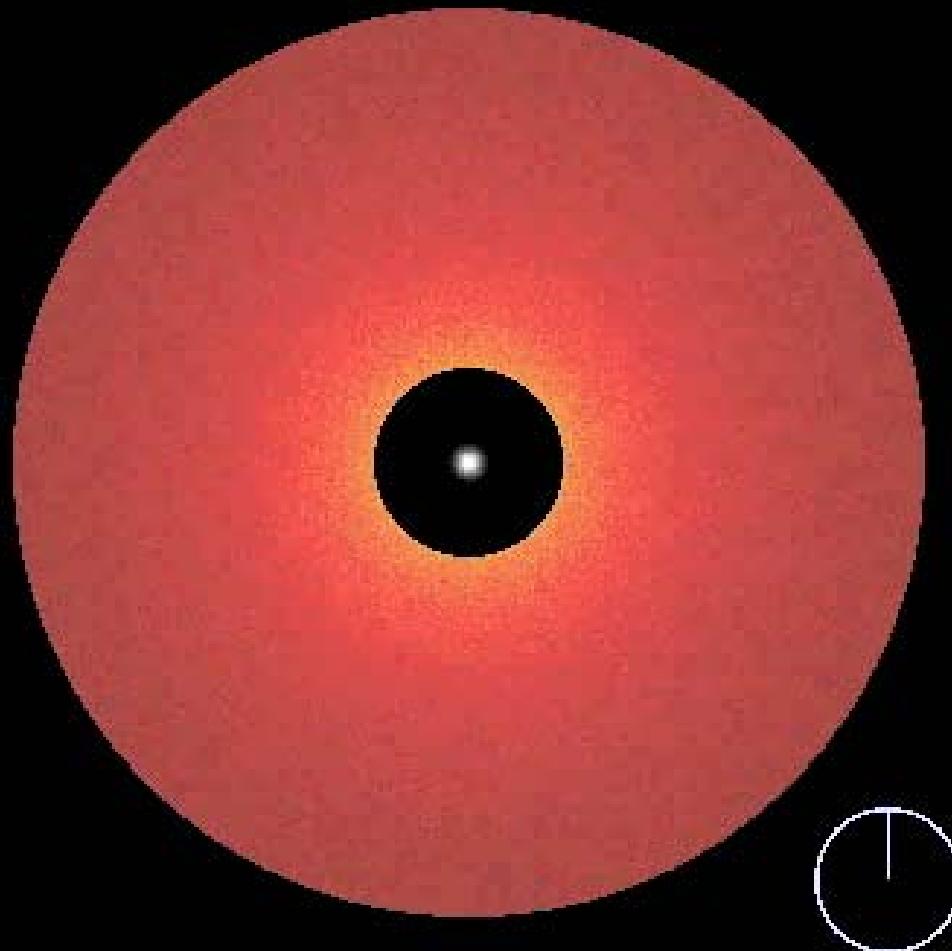
# Debris Disks: The Movies



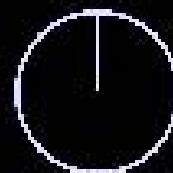
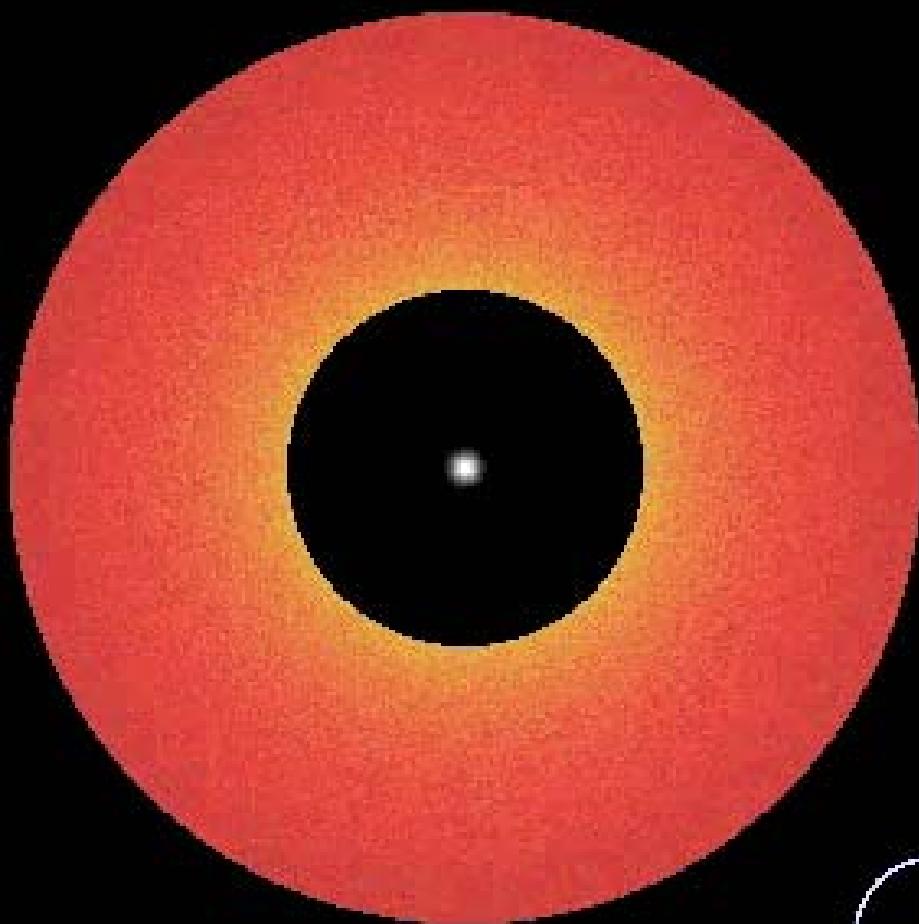
# Bright Rings



# Dark Gaps



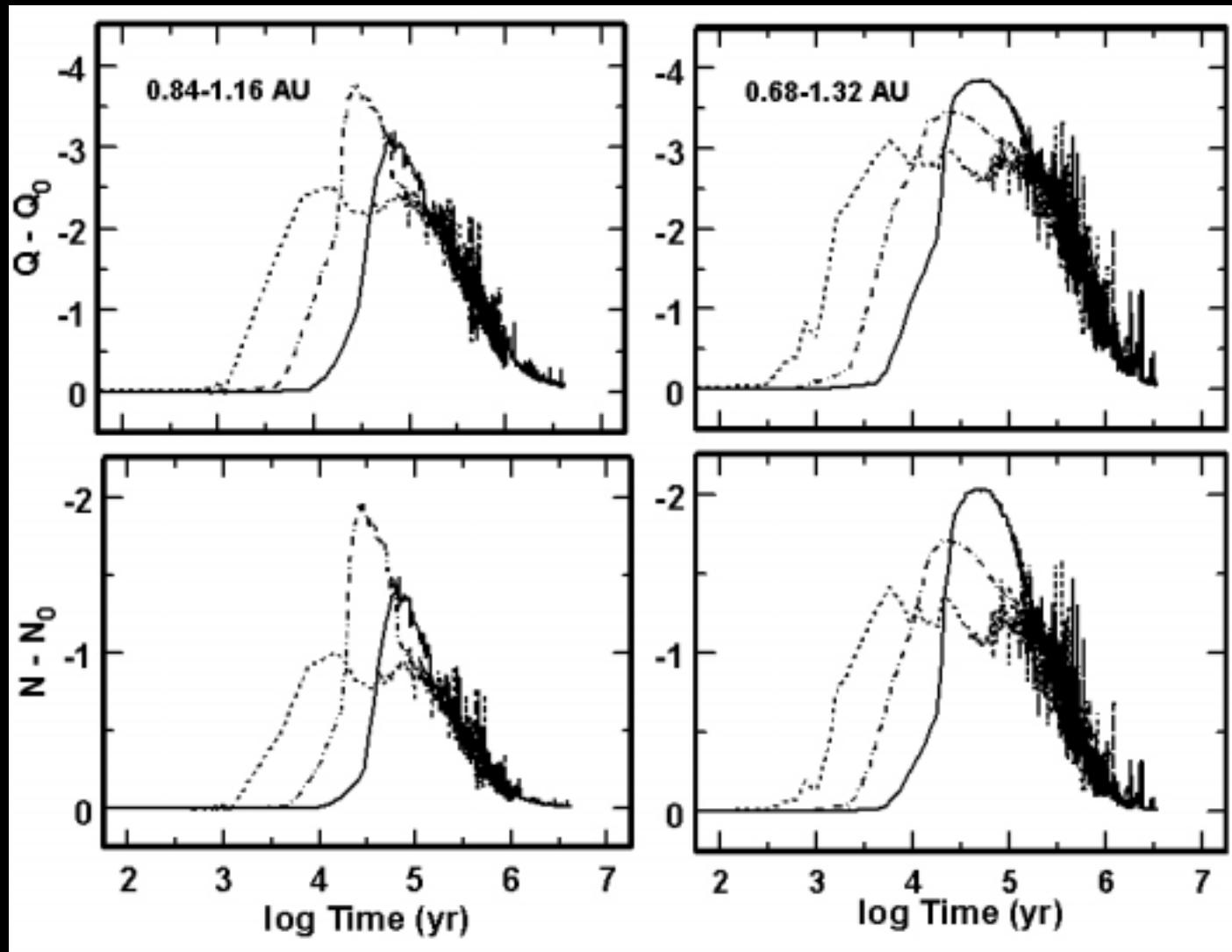
# Companion Stars



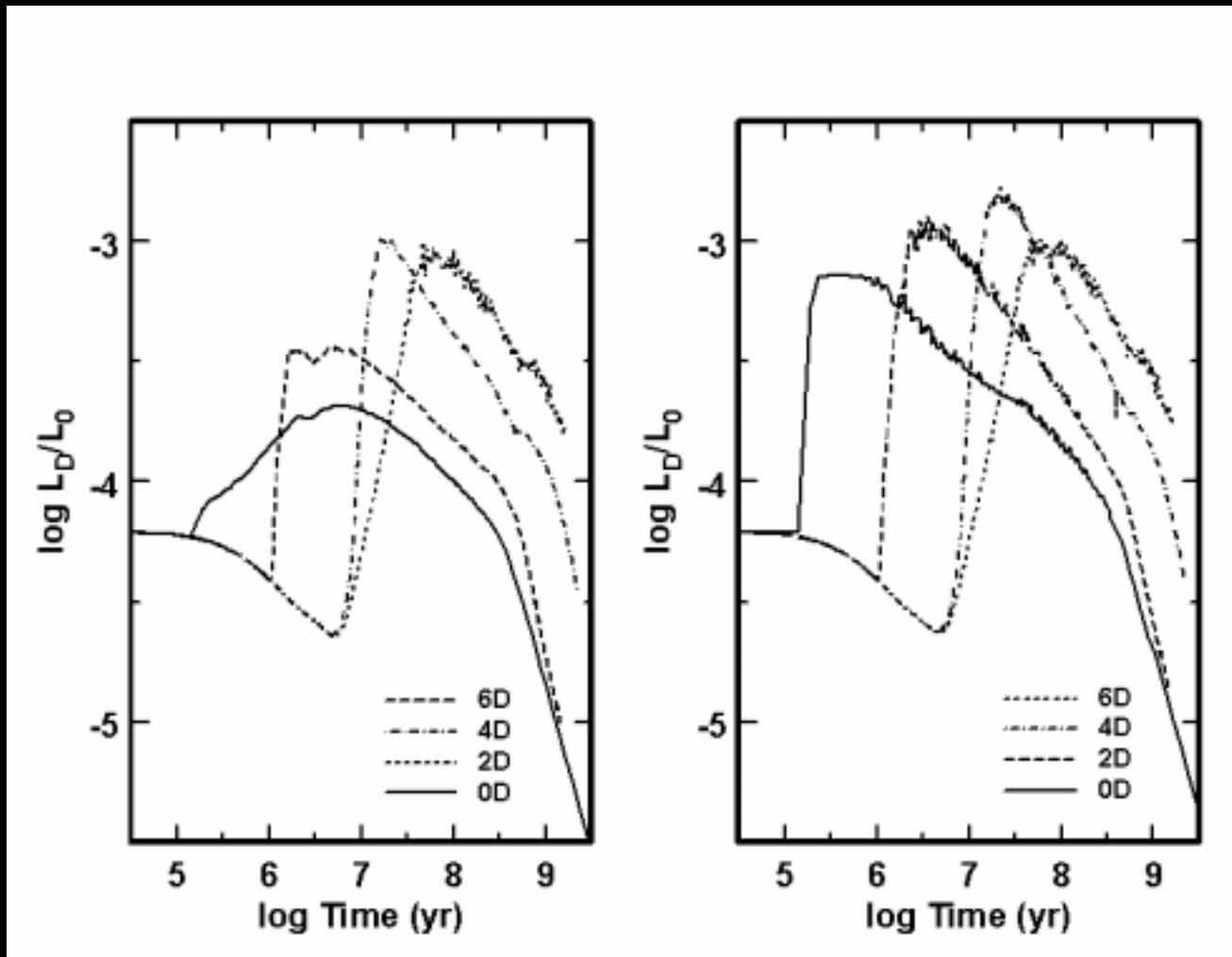
# Dust Mass & Luminosity

- Analytic work – Dominik & Decin
- Numerical work – Kenyon & Bromley
- $L_{\text{dust}} = L_0 / [\alpha_1 + \beta_1 (t/t_0)^n]$      $n = 1 \text{ to } 2$
- $M_{\text{dust}} = M_0 / [\alpha_2 + \beta_2 (t/t_0)^n]$      $n = 1 \text{ to } 2$

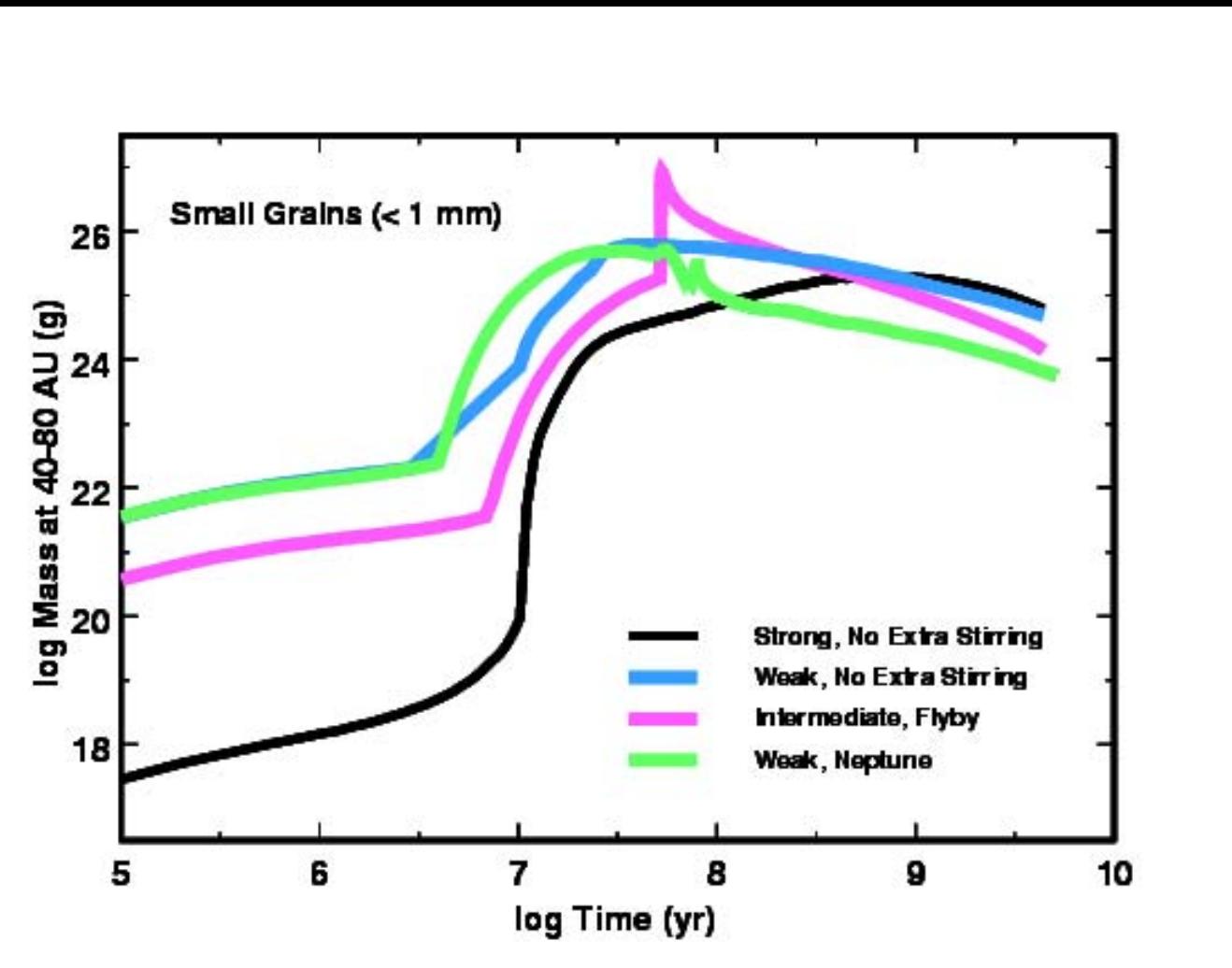
# Dust Luminosity at 1 AU



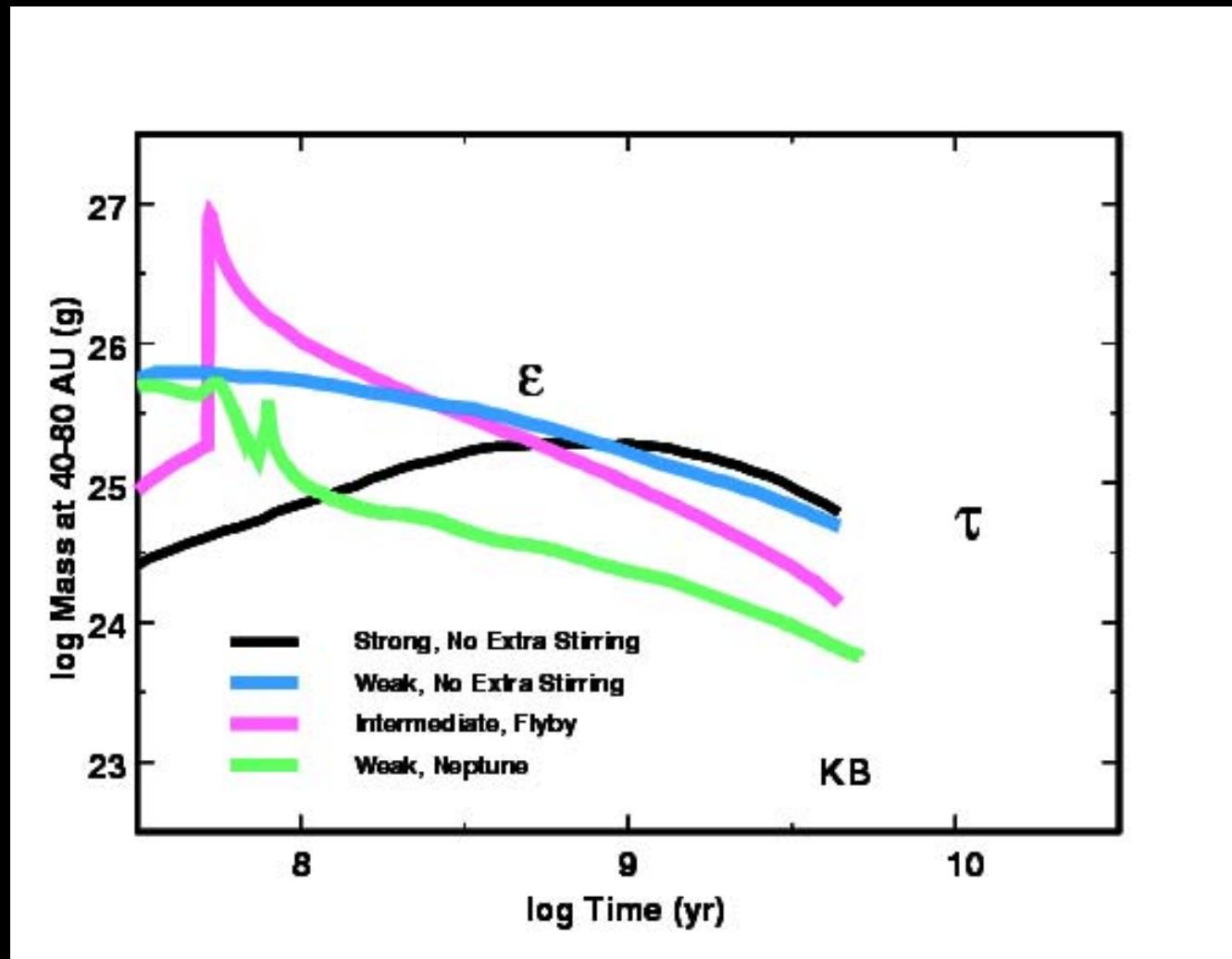
# Dust Luminosity at 100 AU



# Dust Mass at 60 AU



# Dust Mass at 100 AU



# Summary

- **Planet formation yields debris disks**
  - \* Terrestrial zone: 1-10 Myr
  - \* Kuiper belt: 10-100 Myr
  - \* Structures: bright rings & dark gaps
- **Tests of models**
  - \* dust luminosity (declines with age)
  - \* dust temperature (cooler with age)

# Coming Attractions

- **Hybrid code**
  - \* Terrestrial zone + gas giants
  - \* Kuiper belt + gas giants
- **Other additions**
  - \* gas accretion: gas giants
  - \* migration: hot gas giants

# Useful References

Dominik & Decin ApJ 598:626

Greaves MNRAS 351:L99

Greaves et al MNRAS 351:L54

Kenyon et al ApJ, 524:L119

Luu & Jewitt ARA&A 40:63

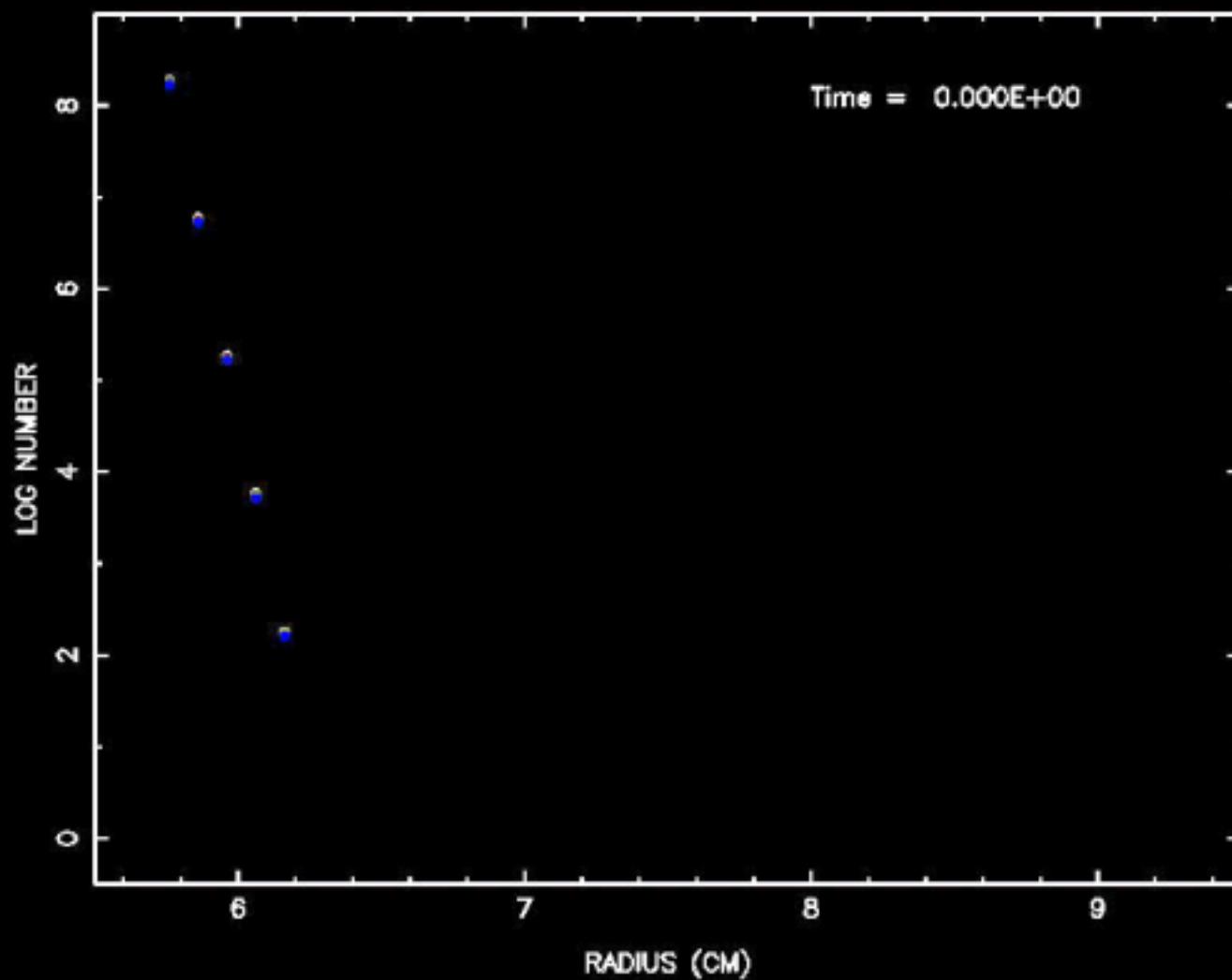
Takeuchi & Artymowicz ApJ 557:990

Weidenschilling et al Icarus 128:429

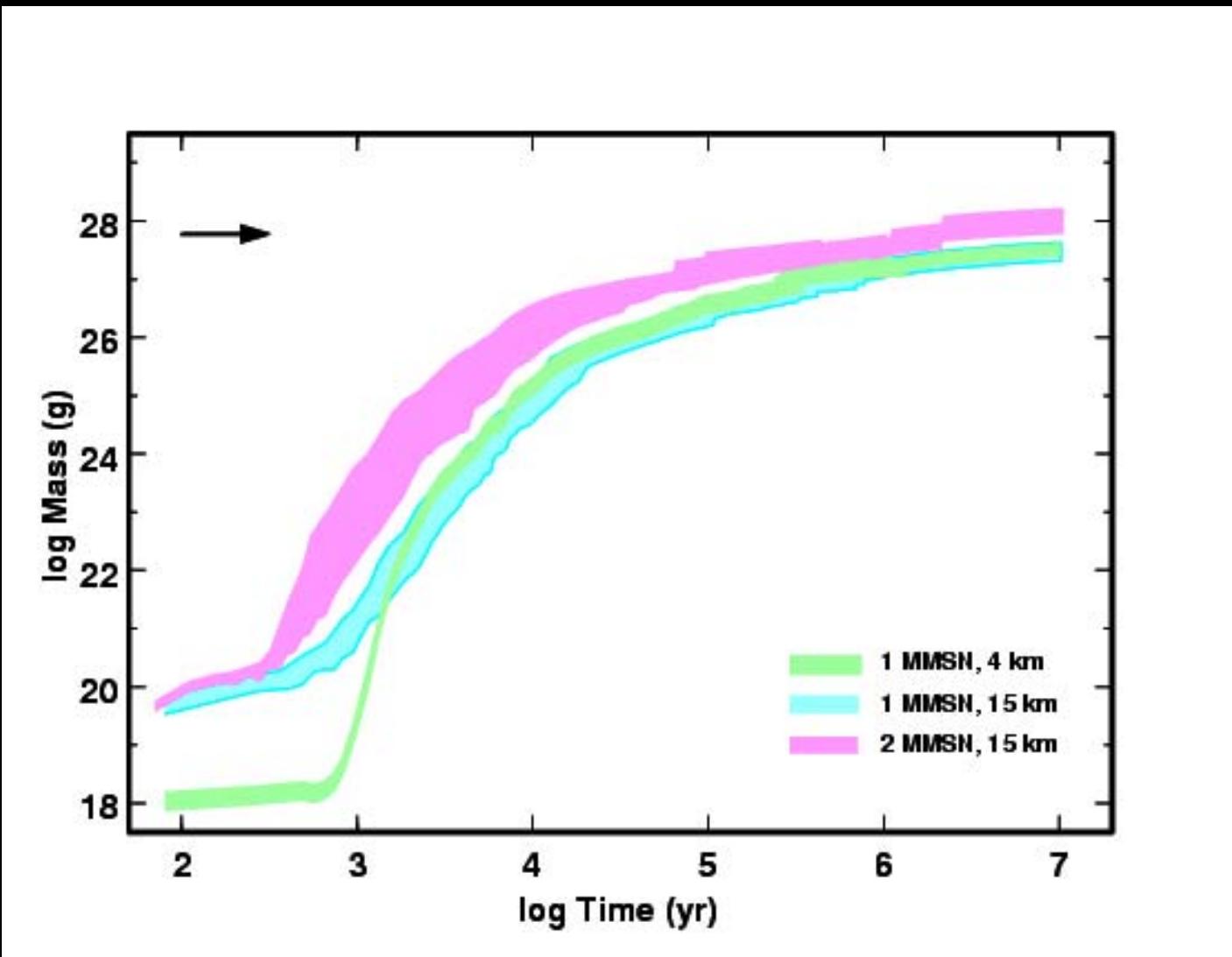
Wetherill & Stewart Icarus 77:330

# Size Distribution

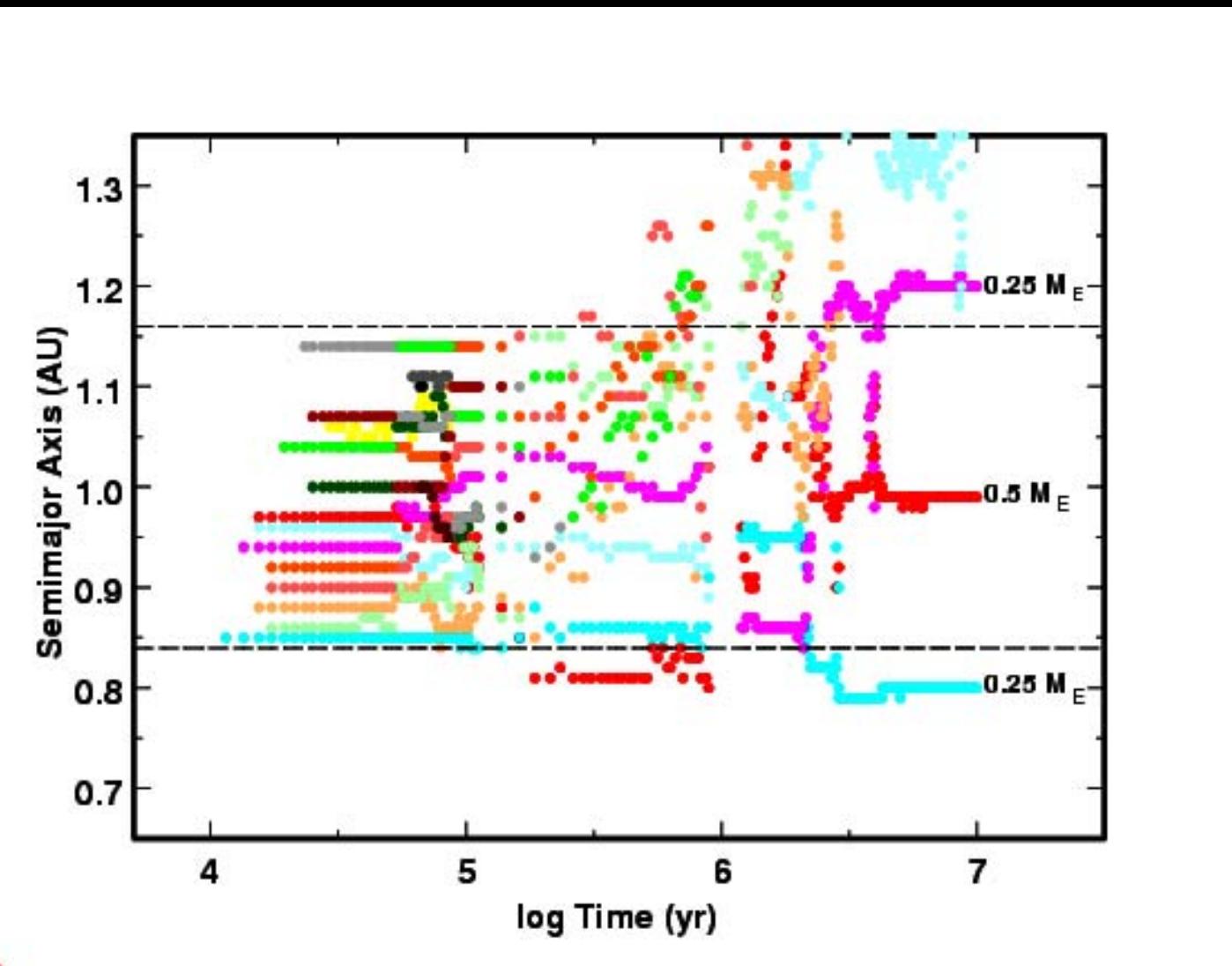
EARTH NBODY



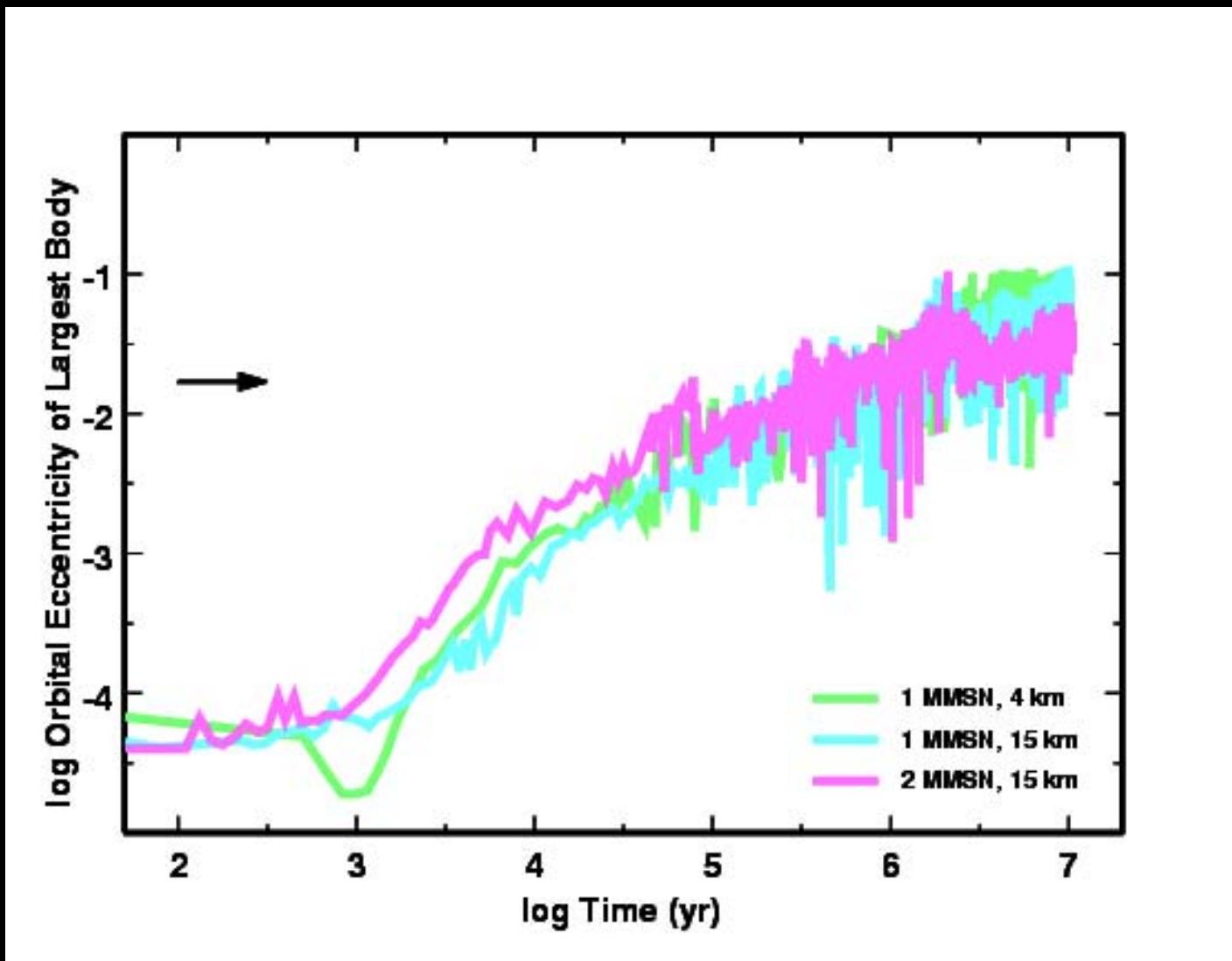
# N-Body Mass



# N-Body Positions



# Eccentricity



# Collision Outcomes

- Energy scaling algorithm
- Merger
  - \* collision energy < binding energy
- Disruption
  - \* collision energy > binding energy

# Mergers



# Disruptions



# Velocity Evolution

- **Viscous stirring**
  - \* all velocities increase
- **Dynamical friction**
  - \* small bodies brake large bodies
- **Gas, Poynting-Robertson drag**
  - \* brake small bodies
- **Collisions**
  - \* brake large bodies

# Dust



# An Asteroid

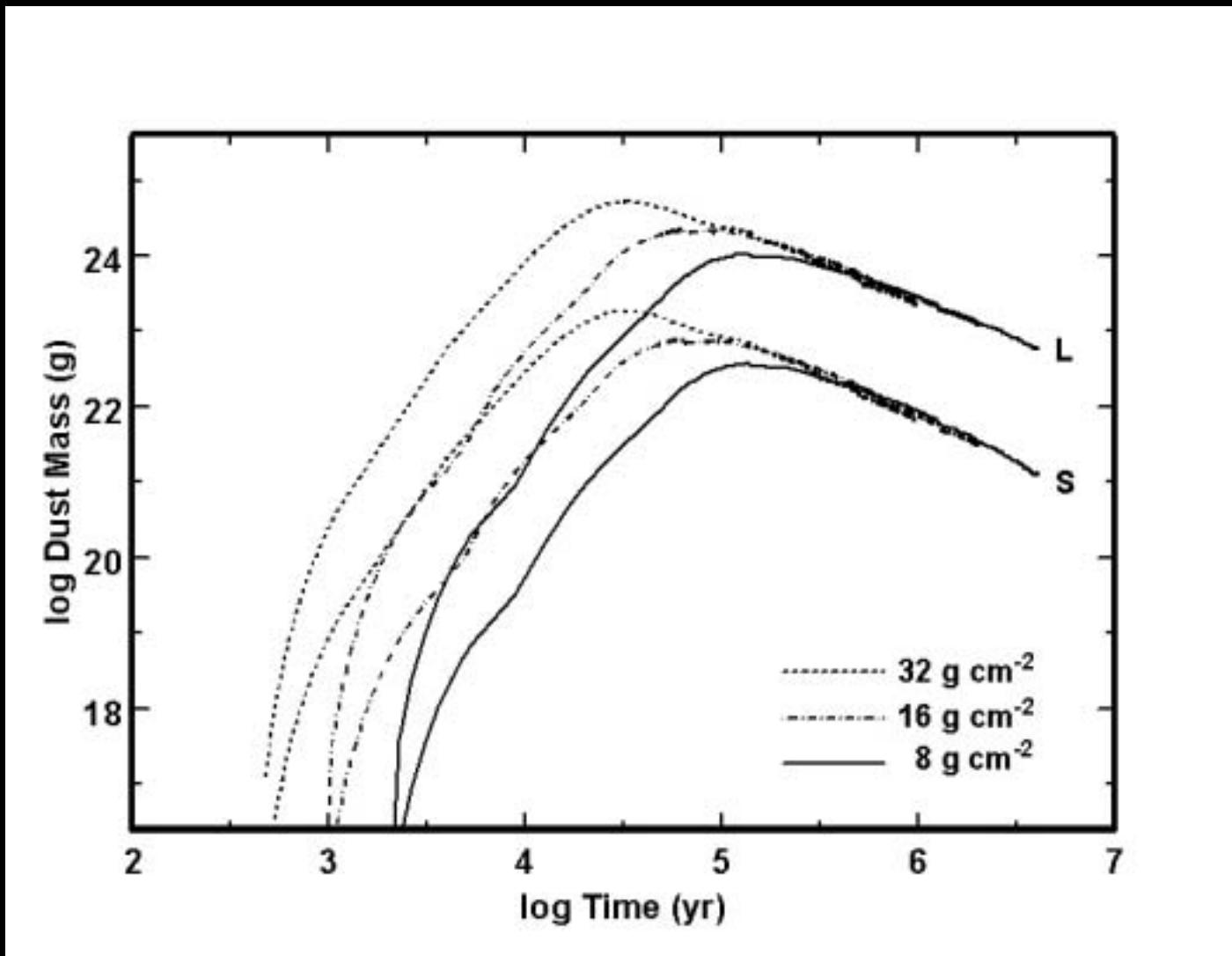
$10^{18}$  to  $10^{21}$  dust grains



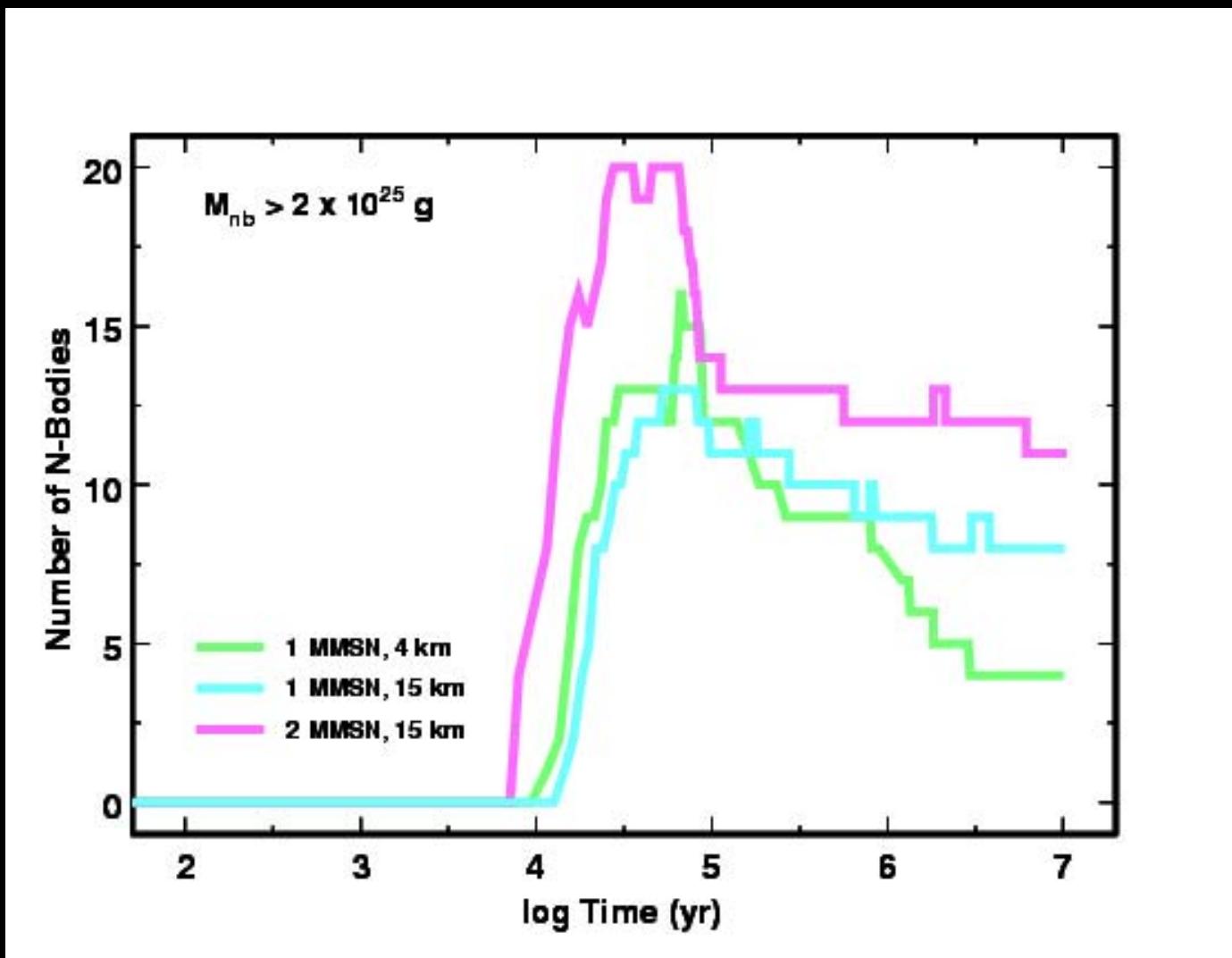
# Three Phases of Growth

- **Slow growth**
  - \* geometric cross-sections
  - \* all bodies grow linearly
- **Runaway growth**
  - \* gravitational focusing
  - \* largest bodies grow exponentially
- **Oligarchic growth**
  - \* largest bodies grow slowly
  - \* collisional cascade

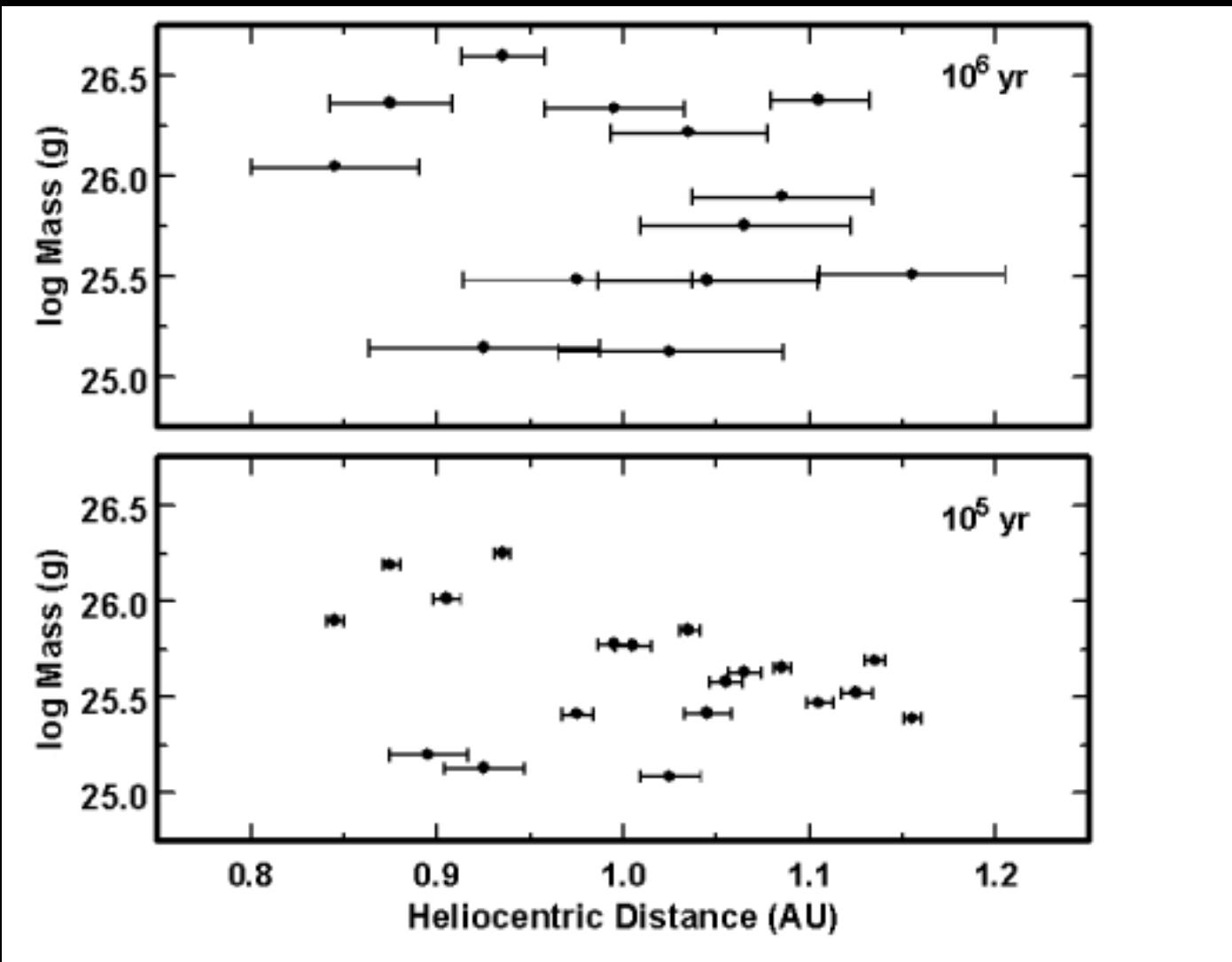
# The Dust Mass



# N-Body Number



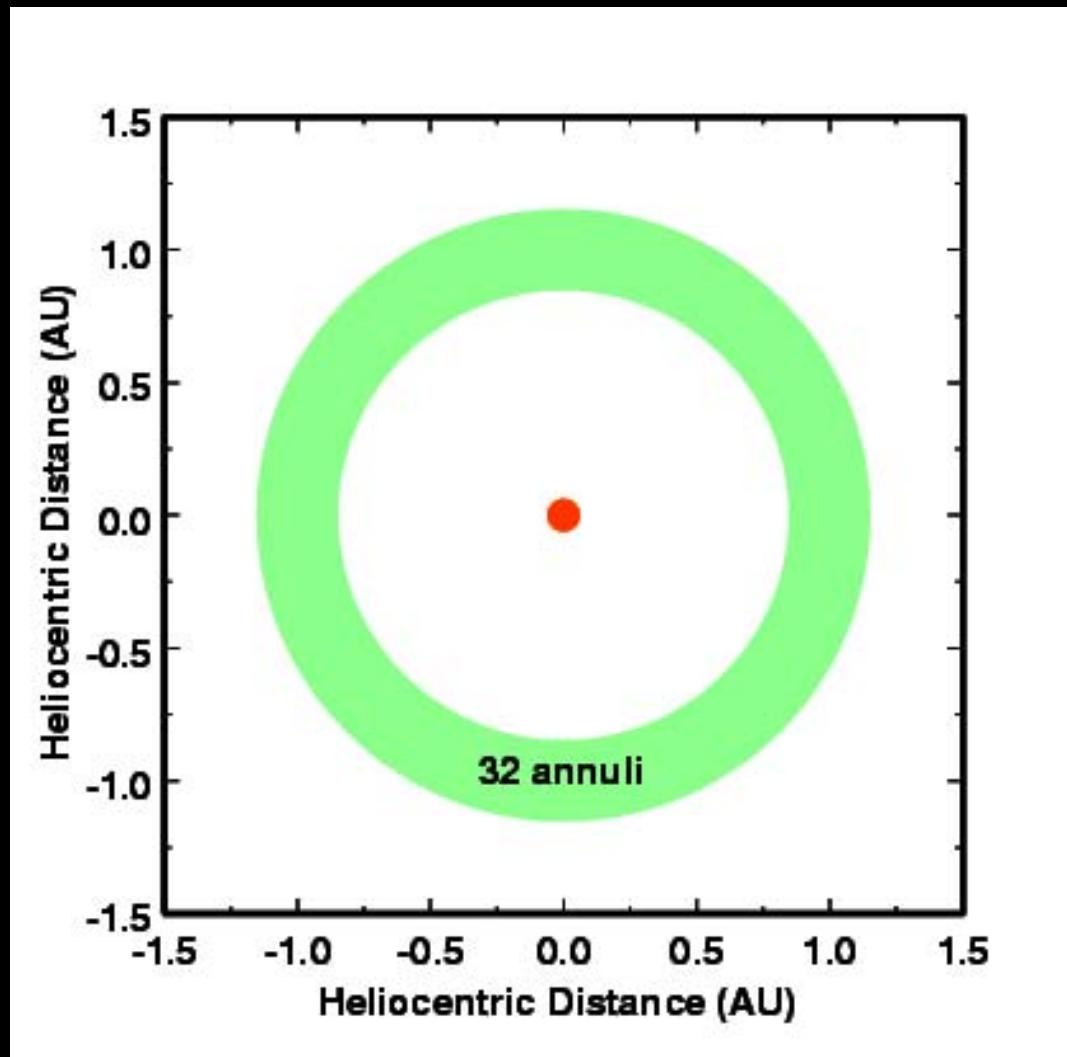
# The Largest Objects



# Planet Formation

- **Dynamical instability**
  - \* part of disk collapses
  - \* gravitational instability
  - \* make Jupiters
  - \* Jupiters stir up debris
- **Earth and Pluto are impossible**
- **Boss, Cameron, ...**

# Our Grid



# Debris Disks

- **Far-infrared emission**
  - \* small dust grains absorb starlight
  - \* reradiate at 100 microns
- **Optical and near-infrared emission**
  - \* grains scatter starlight
- **Disk-like morphologies**
  - \* size of our solar system

# Links to Other Solar Systems

- Our solar system
  - \* 1000's of rocky planets & asteroids
- Other solar systems
  - \* 1000's of debris disks
- Need a robust formation model
  - \* numerical simulation of solar system

# Our Calculations

- **Multiannulus hybrid code**
  - \* 32-64 concentric annuli at 0.5-1.5 AU
  - \* 1 m to 1 km planetesimals
  - \* minimum mass solar nebula
- **Results after 1-10 Myr**
  - \* planets: Moon to Earth
  - \* rings of dust

# Rocky Planets

- **Location**
  - \* close to Sun
- **Size of a rocky planet**
  - \* 100-10000 km radius
- **Types**
  - \* Planets – Mercury, Venus, Earth, Mars
  - \* Asteroids – collision fragments
  - \* Zodiacal light – dusty debris